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Development of a Lab Experiment to Demonstrate Thermodynamic Analysis and Turbine Efficiency

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Abstract

The goal of this project was to develop an experiment that students could perform to learn about the 1st and 2nd law of thermodynamics by working to calculate the thermodynamic efficiency of a Tesla turbine. Currently students have the ability to make theoretical calculations on word problems in a book but would be benefited by the opportunity to interact and take measurements from a turbine physically. Tests on an existing turbine in a WPI flow system were completed to purchase appropriate meters for the ease of future testing. This testing was performed on the system to serve as the backbone for the experimentation that students would perform in order make calculations with gas assumed to be ideal and with the generalized correlations required for the assumption of non-ideal gas. The maximum efficiency that was attained from the turbine was 6% but it was determined that with higher operating pressures, higher efficiencies would be produced.

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Introduction

It is important that developing chemical engineers gain the knowledge of thermodynamics and theoretical knowledge alone is not enough to equip the new breed of engineers that will be entering the work force. Worcester Polytechnic Institute's motto describes it best as "Lehr und Kunst" a German phase meaning "Theory and Practice". In a normal thermodynamics course chemical engineering students study flow systems like turbines and compressors, however this study is limited to theory, word problems, and paper calculations. A typical exercise in thermodynamics is the calculation of turbine efficiency that is defined as the actual work produced by the turbine divided by the maximum possible work that the turbine could produce given the conditions

$$\eta = \frac{W_s}{(W_s)_{isen}} \tag{1}$$

For the case of a turbine the efficiency is equal to the shaft work divided by the isentropic shaft work that would occur if there were no change in entropy. A constant entropy process being one that is for a turbine means adiabatic operation with no losses to friction meaning that no energy in the system is lost and all of it contributes to the work produced. In keeping with the second half of WPI's motto it is necessary to make this exercise more than just the words in a book and to let these students see the spinning fly wheel of the turbine and take electrical readings from a generator that is converting the work produced by the turbine into electrical energy. As shown in Figure 1, there is a Tesla turbine already installed in an air flow apparatus in the Unit Operations Laboratory at WPI. A generator attached to the turbine is connected to three light bulbs and increasing air flow can be observed to increase the light produced. To conduct a thermodynamic analysis on the turbine, it will be necessary to measure the electrical signals coming from the generator as well as the temperature and pressure at the turbine inlet and outlet and the air flow rate. To include this thermodynamic analysis as a practical component of a chemical engineering course, the goals of this project are to 1) install the instruments needed to measure electrical signals coming from the generator connected to the turbine, 2) demonstrate the calculation of actual work from the turbine and the corresponding efficiency that is the result of this, and 3) determine appropriate operating conditions for the lab exercise.

Figure 1: Tesla Turbine in flow system located above the yellow flow valve handle

Background

If this exercise were to be incorporated into a class the device that would be used to generate the power would be as mentioned before a Tesla turbine otherwise known as a bladeless centripetal flow turbine. Impinging blades on a traditional turbine are curved such that fluids striking perpendicular to the blades cause them to rotate and turn the turbine's shaft, producing work. Unlike these traditional designs, Nikola Tesla produced a turbine that would have thin plates spaced a small distance apart that would allow the fluid to flow parallel to the turbine's "blades". This new design adopted a principal of fluid dynamics to create the energy from the fluid flow.

Instead of requiring the raw force of the fluid to push the blades into rotating the new design would make use of the no slip condition whereby the fluid traveling in laminar flow along the surface of the plate would impart a new infinite quantity of friction on the plate and the fluid near it. The friction caused by the fluid slowing to a stop against the plate and being pulled along by the fluid flowing next to it causes the plate to start rotating and causes the shaft to rotate along with the plates creating work that can be harnessed as energy.

In Tesla's view the old method of impinging blades would result in the loss of work as material would be able to miss the blades and thus impart none of their energy to the system. However with the parallel flow model, all of the fluid would pass the blades and impart all the possible energy that the media had to deliver. Another area of concern at the time for the traditional turbine blade was the lack of aerodynamic development that would capture the energy of the fluid efficiently. This would not be a concern for the Tesla turbine as the flat disks would capture the energy of the fluid through friction as the laminar flow moved along the disk.

With these concerns in mind, Tesla set about to produce a turbine that would not lose efficiency in the manner of the classical turbines, the construction of which leading Tesla to claim that “The new [Tesla] turbine offers a striking contrast using as it does practically the entire material of the power-giving portion of the engine. The result is an economy that gives and efficiency of 80 percent to 90 percent.” [1].

Although there remains some controversy over the possibility of implementing Tesla’s turbine design with such a high efficiency, it is generally agreed that these claims may have been erroneous or exaggerated. Small air powered Tesla turbines similar to ours have been reported to have efficiencies more on the order of 30 % [2]. Recent revived interest in Tesla’s turbine that can easily be found on the internet, makes it of particular interest for students to evaluate the thermodynamic efficiency of a turbine and compare to that purported by Tesla.

In order to easily allow students to verify the thermodynamic efficiency of the Tesla turbine it is necessary to install a series of meters that will allow students to record the voltage and amperes produced by the turbine at various levels of fluid flow. With the temperature and flow readings available from the system students will be able to perform calculations for the enthalpy change across the turbine and determine the potential work that could be achieved from the given input. The students will also be able to record the actual work produced by the turbine with the volts and amperes recorded for the various flows. These two calculations coupled together will allow students to find the thermodynamic efficiency of the turbine by comparing the actual work produced and the theoretical work possible considering the change in enthalpy delivered to the system.

Theory

The first law of thermodynamics states that for an open flow system, operating at steady state, the change in enthalpy will be equal to the heat transfer from the system plus the shaft work of the system

$$\Delta H = Q + W_s \tag{2}$$

For an adiabatic case, with no heat loss to the surroundings, this can be further simplified to the change in enthalpy being equal to the shaft work. The shaft work being the only work done in the system this means that in order to solve for the efficiency of the turbine it is necessary to calculate the shaft work as well as the isentropic shaft work. The actual shaft work being calculated by solving for the change in enthalpy that for an ideal gas is equal to the integration of the heat capacity from the inlet to the outlet temperature.

$$\Delta H = W_s = \int_{T_{in}}^{T_{out}} C_P dT \tag{3}$$

The second law of thermodynamics introduces the concept of entropy as a measure of energy that is not available for use due to irreversibility in a process. For an ideal gas the change in entropy is given by

$$\Delta S = \int_{T_{in}}^{T_{out}} C_P dT - R\frac{dP}{P} \tag{4}$$

If a process could be accomplished adiabatically and completely reversibly the entropy change would be zero and the process could be called isentropic. The work done by such a hypothetical process would be the maximum work possible under the given conditions and could be called the isentropic work. For the isentropic work of the system it is necessary to consider the change in entropy to be zero.

$$\Delta S = 0 = \int_{T_{in}}^{T_{isen}} C_P dT - R\frac{dP}{P} \qquad (5)$$

This equation for the change in entropy can be rearranged to solve for the isentropic temperature, $T_{isen,}$ that can then be used for the calculation of the change in enthalpy. The isentropic temperature is the hypothetical temperature that would result if the process was accomplished isentropically. The isentropic enthalpy change, $(\Delta H)_{isen}$, can be calculated using Equation 3 and will be equal to the most work the system could produce with the input conditions. The turbine efficiency can then be calculated as the actual work produced by the system divided the most possible work the system could produce that is also equal to the change in enthalpy divided by the isentropic change in enthalpy

$$\eta = \frac{\Delta H}{(\Delta H)_{isen}} = \frac{W_S}{(W_S)_{isen}} \qquad (6)$$

The enthalpy and work terms in the above equations will have units of J / mol. To obtain the total work produced in a steady flow process it is necessary to multiply by the flow rate in mol / s to yield J / s or watts.

The shaft work for the Tesla turbine is converted into three-phase power, W_e, by an attached generator. With minimal loss of energy in the generator this means that the electrical work from the generator is assumed equal to the shaft work of the turbine and will be used in place of the actual enthalpy change for the calculation of turbine efficiency. Electrical work is normally expressed as watts equals volts times amps. For a three phase generator the work produced in each phase should be multiplied by 3 to obtain the total watts produced. It is often convenient, however, to measure the line voltage instead of the phase voltage [3]. For a typical three phase system, the line voltage is equal to the phase voltage times the square root of 3. When measuring the line voltage, V, in parallel and the current, A, in series, the electrical work from the generator is given by

$$W_e = V \cdot A \cdot \sqrt{3} \tag{7}$$

In order to do a further analysis of the Tesla turbine, it is necessary to consider the air running the system to be a non-ideal gas and this requires the addition of generalized coefficients. The equations for the change in enthalpy and entropy for non-ideal gases are shown below

$$\Delta H = \int_{T_{in}}^{T_{out}} C_P^{ig} dT + H_2^R - H_1^R \tag{8}$$

$$\Delta S = \int_{T_{in}}^{T_{out}} \frac{C_p^{ig}}{T} dT - R ln \frac{P_{out}}{P_{in}} + S_2^R - S_1^R \tag{9}$$

It is first necessary to solve for the generalized coefficient H_1^R that requires the use of reduced temperatures and pressures so it is first necessary to define the critical temperature and pressure of air T_c (K)= 132.2 and P_c (Bar)=37.45 and then the reduced temperature and pressure for the inlet condition if calculated by dividing the temperature and pressure by the critical temperature and pressure. The reduced temperature and pressure are used to determine H_1^R / RT_c from the Lee/Kesler Generalized-correlation Tables [4]. This is then simplified to H_1^R with the gas constant and the critical temperature of air below

$$H_1^R / RT_c \cdot R \cdot T_c = H_1^R \tag{10}$$

The second generalized correlation that is calculated S_1^R is completed in the same manner as the previous correlation. The reduced pressure and temperature for the inlet condition are input into the Lee/Kesler Generalized-correlation Tables to get the value for S_1^R / R and is then reduced to the required value using the gas constant. An initial estimate for

${S_2^R}/{R}$ is then found from the Lee/Kesler Generalized-correlation Tables by using the reduced temperature calculated with the outlet temperature from the ideal gas case and this estimate will be corroborated shortly using the equation for the change in entropy. The reduced pressure uses the outlet pressure that in this case is the atmospheric pressure. As stated before the two generalized correlations for entropy are input into the equation for the change in entropy assuming an isentropic case such that the change in entropy will be zero that is rearranged below to solve for the outlet temperature as was the case for ideal gas using goal seek in Microsoft Excel

$$(AlnT_{out} + BT_{out} - 0.5DT_{out}^{-2}) - (AlnT_{in} + BT_{in} - 0.5DT_{in}^{-2}) = ln\frac{P_{out}}{P_{in}} + S_2^R - S_1^R \qquad (11)$$

This new outlet temperature found using the generalized correlations is used to re-calculate the residual temperature that is used along with the Lee/Kesler Tables to find a value for S_2^R and if this value is close enough in value to the first value of S_2^R it is not necessary to re-evaluate the outlet temperature again. The new value for reduced temperature can be used to find the value of H_2^R in the same manner as before with the Lee/Kesler Tables. With the generalized correlations for enthalpy found the change in enthalpy can be calculated with the addition of the correlations and multiply it by the molar flow rate to find the adjusted change in enthalpy. The work output by the generator can then be divided by the isentropic change in enthalpy that includes the generalized correlations to find the turbine efficiency and this new efficiency can be compared to the ideal case.

Methodology

Equipment

Figure 2 shows a schematic diagram of the parts of the existing air flow system required to study the turbine. Compressed air produced in a compressor in the basement of Goddard Hall is available in the house air line at pressures that vary from 65 to 80 psig. A pressure regulator installed in the air flow system allows regulation of pressure between 0 and 60 psig. The systems allows for continuous air flow in excess of 11 SCFM, but at that flow rate the maximum operating pressure is about 30 psig. The existing air flow experiment also has pressure gauges that read up to 60 psig with increments of 0.5 psig, an Omega Engineering FL-1503A rotameter measuring % of 10.45 SCFM and type J thermocouoples connected to a computer for readout using Labview software. Flow rates in CFM measured at the rotameter pressure must be adjusted to SCFM as explained in the appendix.

The existing Tesla turbine was purchased from Gyroscope.com. It came equipped with a Himax HC2812-1080 brushless outrunner motor that was connected to 3, 20 W G4 halogen light bulbs to provide an electrical load. Documentation on the turbine supplied by the manufacturer is provided in an appendix [5]. 10 W and 5 W light bulbs were purchased from a local hardware store and substituted for the 20 W bulbs for some experiments. An Extech Instruments True RMS Model 430 multimeter was used for initial measurements of volts, amps, and hertz. Accurate electric meters with digital readouts and the capability to connect to a computer were purchased from Laurel Electronics. These included a model L10002MRV3 voltmeter, a model L10006MRA4 ammeter, and a model L50002-FR frequency meter.

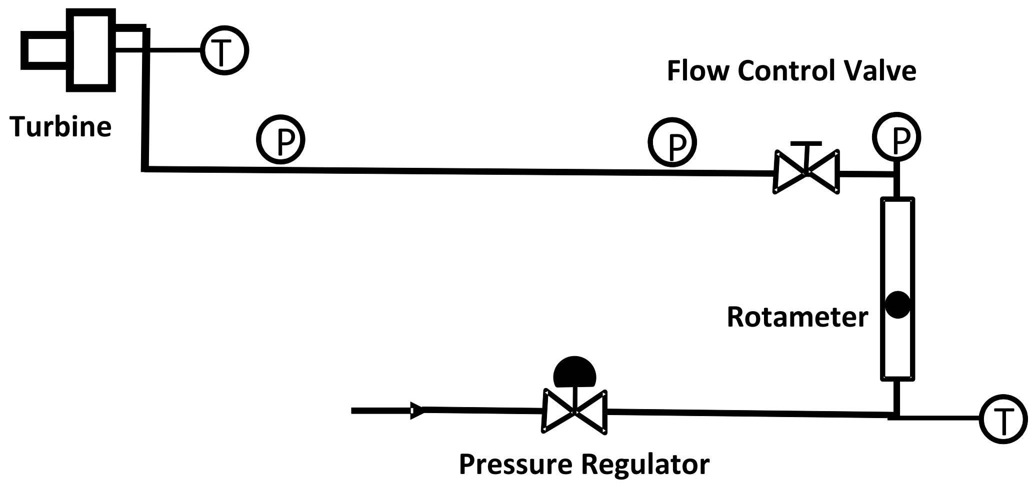

Figure 2: Schematic diagram of turbine portion of air flow apparatus

Initial measurements

Initial tests were performed on the system to evaluate what ranges would be required for the equipment that was to be purchased. For these tests a multimeter was used in parallel coming from the generator to the load to measure the volts put out by the generator and the multimeter was used in series to find the amperage from the generator. The multimeter was also used to find the Hertz or cycles per second of the turbine that could be converted to the revolutions per minute that could be used to observe safe operation of the turbine. These readings were taken with the highest possible flow in order to find the high end of the range for the variables. The tests were performed with three different watt light bulbs in order to find the optimal load that the electricity from the generator would power as different loads result in different outputs from the turbine.

Accurate meter installation

Meters of the appropriate ranges were purchased from Laurel Electronics. The volt and frequency meters were wired in parallel and the ammeter in series. Software was installed on a computer that also took measurements of temperature from thermocouples in lab view that would communicate with and record the data from the ammeter. The other two meters were meant to communicate with the ammeter and be recorded by the computer as well although this has proved unsuccessful so far.

RPM measurements and frequency meter calibration

The initial measurements of frequency and thus RPM were far too high to be the actual revolutions in the turbine and it was necessary to take a reading of the flywheel in the turbine to determine the accurate RPM reading. This was accomplished by removing the cover from the generator portion of the turbine and using a tachometer to measure the actual revolutions of the flywheel. From this a correlation was derived from the readings on the frequency meter to the actual revolutions in the turbine recorded by the tachometer.

Work and efficiency calculations

The pressure regulator and flow control valve were adjusted in order to run the system at different operating conditions and determine the effect on work produced by the turbine and thus the turbine efficiency. The inlet and outlet temperatures were measured using thermocouples in the flow system. The operating pressure of the turbine as well as the rotameter reading and pressure reading at the rotameter were used to determine the flow in the system. The volts, amps, and RPM output by the generator were also recorded. These values were used in conjunction to determine the electrical work along with the actual change in enthalpy to corroborate this value. The isentropic change in enthalpy was also calculated and used with the electrical work to find the turbine efficiency.

Results and Discussion

Initial measurements

Testing was completed to find the range that was necessary for the volts, amps, and frequency that would be produced output by the generator. A multimeter was used for the testing and Figure 3 demonstrates the arrangement used for taking a reading of volts from the generator.

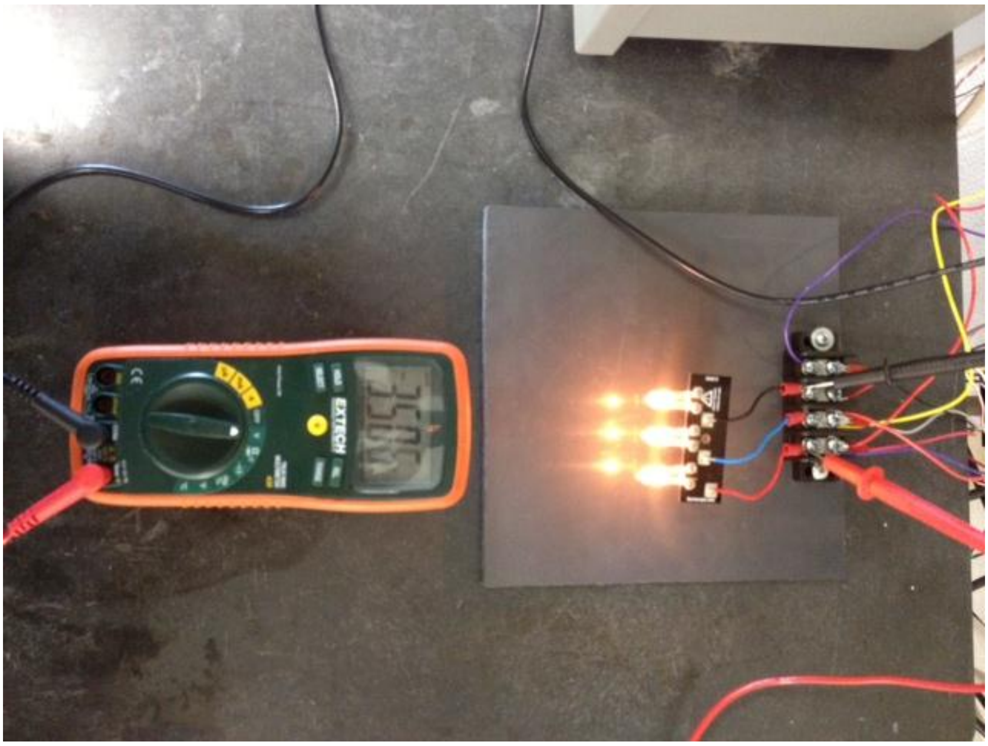

Figure 3: Demonstration of multimeter configuration for recording of volts

Testing was done on the three different watt light bulbs to see how the output would differ when the turbine was run at the highest possible flow and resulted in the values recorded in Table 1.

Table 1: Initial recorded values for the necessary range on meters

Bulb (Watt)	Amps	Volts	Watts	Hertz
5	0.96	9.2	15.3	1647
10	2.08	6.2	22.3	1149
20	3.25	4.1	23.1	841

The 5 watt bulbs lit up the best out of the three possible choices because of the low watts required to power them. This low watt requirement also translated to a low amp output, however. The 10 and 20 watt bulbs resulted in similar power output by the generator, however, due to the high wattage demand of the 20 watt bulbs they did not light up well even at the highest flow possible and as such were a poor visceral demonstration of the changing output produced by the changing flow in the system. This left the 10 watt bulbs as the best option to proceed with and as such dictated the upper range of what was required for the meters.

Accurate meter installation

The initial results shown in Table 1 dictated that an ammeter that can measure up to 5 amps and a voltmeter that can measure up to 20 volts were needed and these were purchased from Laurel Electronics. The frequency meter that was also purchased from Laurel can measure frequencies between 0.0005 Hz and 1 MHz. These meters were installed and are shown operating at a low, medium, and high flow in Figure 4.

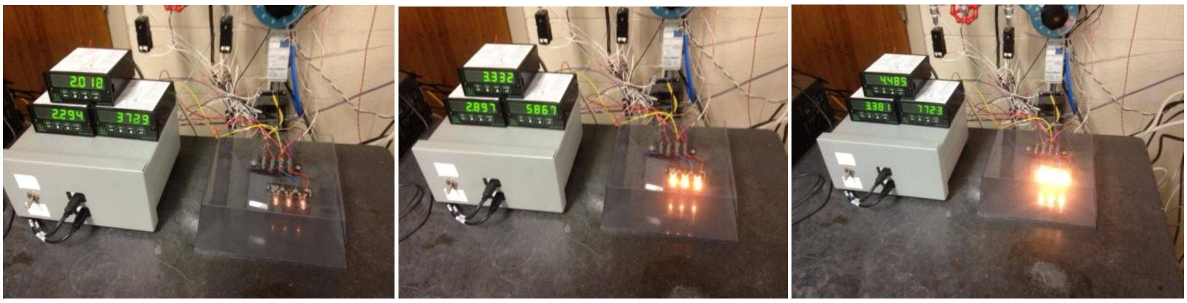

Figure 4: From left to right, installed Laurel meters reading values for low, medium and high flows

RPM measurements and frequency meter calibration

The multimeter measurements made in Table 1 are of Hertz and as such should be a measurement of cycles per second in the turbine and this value could then be multiplied by 60 to reach the RPM of the turbine. If this was the case, however, as the table shows the RPM of the three runs would be 98820, 68940, and 50460 respectively all well above the manufacturer's suggested maximum value of 20,000 RPM. The cover of the generator was removed so that a tachometer could be used to measure the actual RPM of the turbine as shown in Figure 5. Representative measurements are shown in Table 2.

Figure 5: Tachometer measuring RPM on turbine shaft

Table 2: Correlation of Hertz to actual RPM in turbine

RPM	Hz	Ratio
4502	525	8.575
6235	727	8.576
8237	963	8.553

This shows that the conversion of Hertz to RPM for this generator is really by a factor of 8.57 rather than the believed 60. This results in a value of 60/8.57=7 electrical signal cycles per turbine revolution. The details of how the electric generator produces the electrical current are beyond the scope of this study but multiple electrical signals per revolution are to be expected. The aluminum cover over the generator was replaced with one made of Lexan to allow students to view the rotating turbine shaft in the future.

Work and efficiency measurements

The main results for electrical work and turbine efficiency at various operating conditions are shown in Table 3. Raw data and intermediate results are provided in an appendix. It can be seen in Table 3 that the highest efficiency attained with the assumption of ideal gas was 6.18%. While it was understood that Tesla may have overstated the effectiveness of his invention, or that the turbine used was not the most efficient possible, it was expected from reference 2 that the efficiency might be on the order of 30%.

Table 3: Electrical work and efficiency at various operating conditions

	Run1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7
Operating pressure (psig)	3.75	6.25	9.5	12.5	16	20	23
Air flow (SCFM)	3.41	4.55	5.65	6.78	7.68	8.97	10.05
Electrical work (W)	0.017	0.144	0.700	2.970	8.511	16.121	24.429
Turbine efficiency (%)	0.05	0.20	0.54	1.63	3.50	4.95	6.18

One possible explanation for the lower than expected efficiency is that the air in the system may not have behaved as an ideal gas. As shown in the appendix on non-ideal gas calculations, however, the ideal gas assumption had little effect at the operating conditions and the highest efficiency considering non-ideal gas was calculated to be 6.19%.

Another possible explanation for the lower than expected efficiency was the inability to achieve higher operating pressures and flow rates. As shown in Figure 6, the air flow rate was proportional to the operating pressure. Based on the operating principle of the "bladeless" Tesla turbine, it makes sense that the electrical work increases with increasing air flow (and operating pressure) as shown in Figure 7. This dramatic increase in work output with increasing pressure might be expected to lead to a similar increase in efficiency.

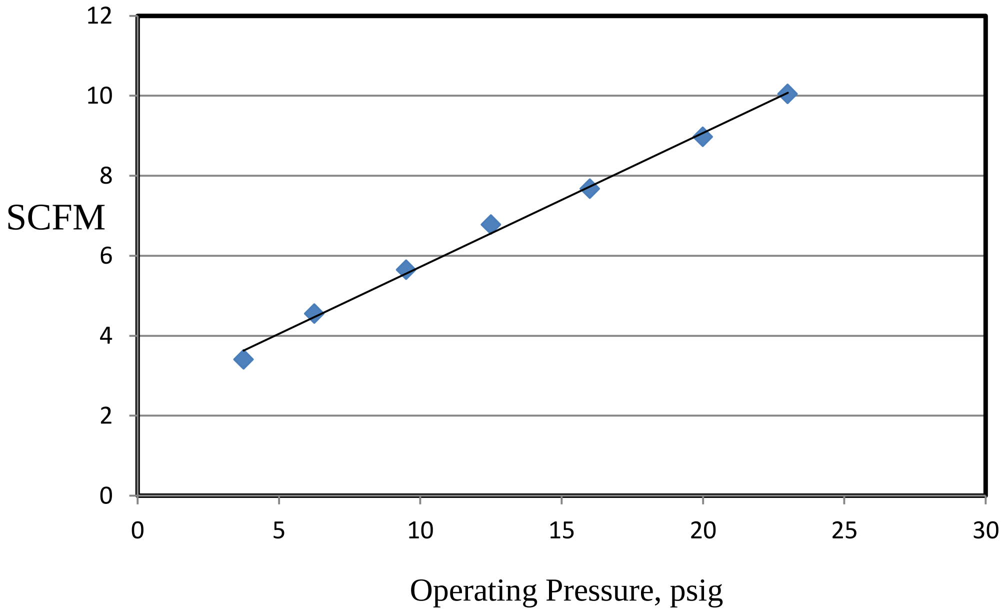

Figure 6: Air flow rate as a function of operating pressure

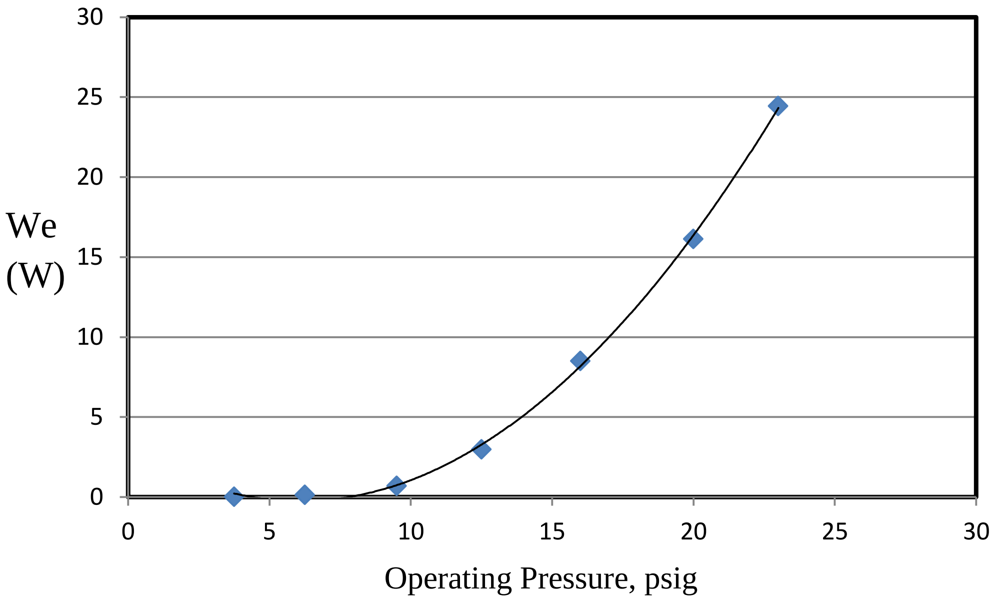

Figure 7: Electrical work as a function of operating pressure

On the other hand, the isentropic work also increased with operating pressure as shown in Figure 8, causing only a modest increase in efficiency with increase in pressure as shown in Figure 9. Nevertheless, it might be expected that an efficiency of close to 30 % could be achieved if the operating pressure were increased to 65 psig as given by reference 2.

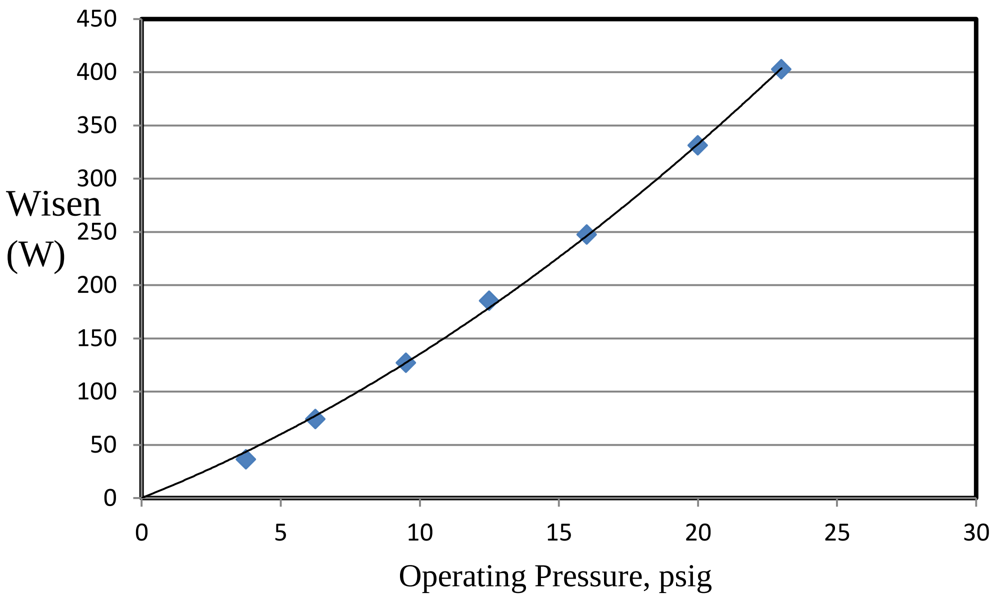

Figure 8: Isentropic work as a function of operating pressure

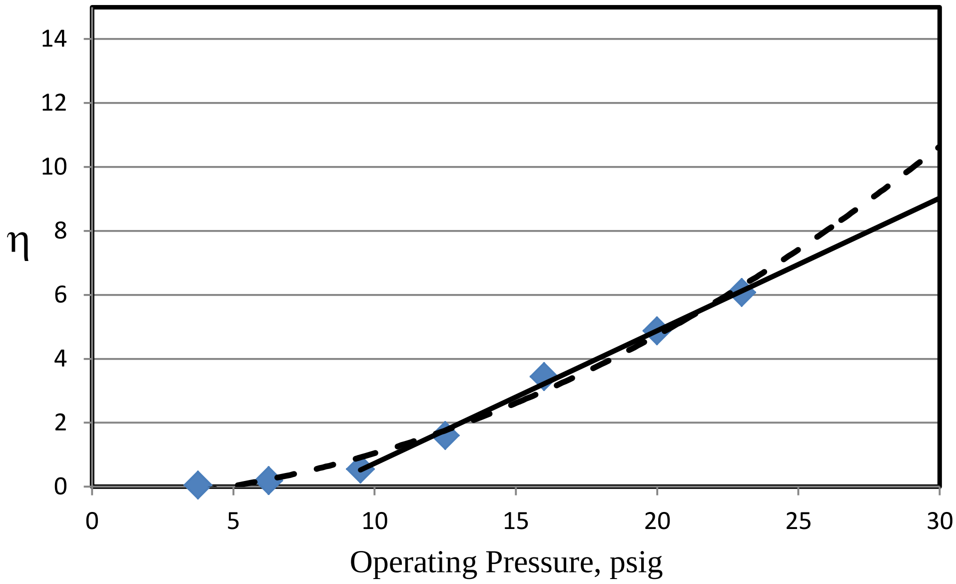

Figure 9: Turbine efficiency as a function of operating pressure

A sample calculation presented in the appendix shows that with the data given by reference 2 of We = 139 W, operating P = 65 psig, and flow rate equal to 10.94 SCFM the turbine efficiency as defined here would be 20.2 %. The turbine described in reference 2 is not the same as that used here. Using the data given by the manufacturer (provided in the appendix) it is anticipated that 150 W could be generated at a flow rate of 9.5 CFM at about 60 psig with our turbine. The standard cubic feet per minute flow under these conditions would be 21.4. The turbine efficiency under these conditions was calculated and found to be 11.2 %.

For more optimal performance of the turbine it would be good to install a dedicated high capacity compressor so that the turbine could receive higher pressure and flow and the efficiency could be improved. Another option to increase the work produced and possibly the efficiency would be to heat the air before it enters the turbine using heating tape on the outside of the pipe or an inline heater. Heated air would have a lower density and a higher velocity. Unfortunately, time constraints precluded testing if this would improve performance.

Conclusions and Recommendations

In order for the students to get a thorough understanding of the effect the operating conditions have on the turbine's efficiency it is recommended that they take readings with a low flow that just begins operating the turbine, a medium flow, and a high flow for the system. With these readings the calculations the students do will be able to demonstrate the importance of pressure on turbine efficiency as well as the variance in power production with respect to amount of flow. Although it is desirable to demonstrate high efficiency, based on the above results, it is difficult to justify installing a dedicated high pressure, high flow capacity air compressor that would be required to double or possibly triple the measured turbine efficiency. Having students measure efficiencies at low to moderate pressures and then calculate efficiencies at higher pressures seems appropriate.

To facilitate data collection and control of the process, it might be advisable to move the turbine's location along with the power meters closer to the rotameter for ease of calculations; and to potentially move the locations of the thermocouples to get a better reading of the inlet and outlet temperatures. It would also be of interest to test whether or not heating the air before it enters the turbine could improve performance.

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Appendix

Raw data

Table 4: Raw data recorded during runs

	Run1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7
Volts (V)	0.063	0.189	0.49	1.49	3.22	4.988	6.6
Amps (A)	0.152	0.44	0.789	1.151	1.526	1.866	2.137
Flow rate (% 10.45 SCFM)	15	20	25	30	34	40	45
Correction pressure (PSI)	55	55	54	54	54	53	52.5
Operating pressure (PSI)	3.75	6.25	9.5	12.5	16	20	23
Outlet temperature (°C)	21.21	21.21	21.085	20.665	19.815	19	18.27
Inlet temperature (°C)	22.39	22.37	22.33	22.315	22.45	22.485	22.54
Cycles (RPM)	NA	NA	NA	2,571	5,246	7,971	10,457

Calculated results

Table 5: Results that were calculated or corrected from runs

	Run1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7
Actual flow rate (SCFM)	3.413	4.551	5.648	6.777	7.681	8.97	10.054
Actual flow rate (Mol/s)	0.066	0.088	0.109	0.131	0.149	0.174	0.195
Actual ΔH (J/s)	2.275	2.982	3.971	6.315	11.429	17.652	24.240
Actual ΔS (J/sK)	0.117	0.249	0.440	0.650	0.872	1.181	1.442
Tisentropic (K)	276.961	267.039	256.171	247.686	239.301	230.973	225.535
Electrical work (J/s)	0.017	0.144	0.700	2.970	8.511	16.121	24.429
Isentropic work (J/s)	35.752	73.002	124.893	182.002	242.837	325.423	395.275
Turbine efficiency	0.05%	0.20%	0.54%	1.63%	3.50%	4.95%	6.18%

Sample Calculation for ideal gas

In order to calculate the turbine efficiency for an ideal gas it is first necessary to calculate the isentropic change in enthalpy that will be the most energy that could possibly be derived from the inlet air. The outlet temperature that would result if the turbine operated isentropically, T_{isen}, is found using the equation for the change in entropy for an ideal gas. The entropy change will be equal to zero for isentropic operation.

$$\Delta S = \int_{T_{in}}^{T_{isen}} \frac{C_p^{ig}}{T} dT - R ln \frac{P_{out}}{P_{in}} = 0$$

That can be rearranged as is shown below

$$\int_{T_{in}}^{T_{isen}} \frac{C_p^{ig}}{T} dT = 8.314 * ln \frac{14.7}{37.7}$$

The function of C_P/R represented below for air with the values of A, B, and D found in appendix C.1(Smith, Van Ness, Abbott. 2005)

$$C_p^{ig} / R = A + BT + DT^{-2}$$

Thus the equation solving for T_{out} becomes

$$8.314 * \int_{T_{in}}^{T_{isen}} \frac{A}{T} + B + DT^{-3} dT = 8.314 * ln \frac{14.7}{37.7}$$

This simplifies to the following and the outlet temperature was then solved using goal seek in Microsoft Excel

$$(A ln T_{isen} + BT_{isen} - 0.5DT_{isen}^{-2}) - (Aln * 295.69 + B * 295.69 - 0.5D * 295.69^{-2}) = ln \frac{14.7}{37.7}$$

The next value required to calculate the isentropic change in enthalpy is the flow rate that is running the turbine. This is accomplished by taking a reading off of a flow meter that records the percent of 10.45 SCFM flow that is in the system with a corresponding correction pressure. The following equation is then used to calculate the actual flow to the turbine.

$$Q_A = 10.45 * 0.45 * \sqrt{\frac{52.5 + 14.7}{14.7}} = 10.05\ SCFM$$

Normally temperature also factors into this equations however the case will be assumed to isothermal with no change of temperature in the piping thus causing the temperature values to be dropped. The flow rate that is obtained from this equation is in standard cubic feet per minute and it is necessary to convert this value to kilograms per second to conform to the other units in the change in enthalpy calculation and this is achieved using the equation below with a density of air being assumed at 1.19 kg/m^3 for the ranges of temperature involved. Finally in order to make the flow rate a molar flow rate we divide by the molar mass of air.

$$n = 10.05 * \frac{ft^3}{min} x \frac{0.0283\ m^3}{ft^3} x \frac{1.19\ kg}{m^3} x \frac{min}{60\ sec} x \frac{mol}{0.02897\ Kg} = 0.195\ mol/s$$

This flow rate along with the molar heat capacity will leave the change in enthalpy units of Joules per second that can be compared to the actual work output by the turbine and thus allow for a calculation of the efficiency of the turbine. With the flow rate and the outlet temperature calculated all the is necessary is to solve for the isentropic change in enthalpy using the equation below

$$(\Delta H)_{isen} = 0.195 * \int_{T_{in}}^{T_{isen}} C_P^{ig}\, dT$$

That again with the function for C_P/R results in the following

$$(\Delta H)_{isen} = 0.195 * 8.314 * \int_{T_{in}}^{T_{out}} A + BT + DT^{-2} dT$$

This simplifies to the following

$$(\Delta H)_{isen} = .195 * 8.314 * \left(\left(AT_{isen} + \frac{B}{2} T_{isen}^2 - \frac{D}{T_{isen}} \right) - \left(A * 295.69 + \frac{B}{2} * 295.69^2 - \frac{D}{295.69} \right) \right)$$

$$= -395.275 \, \frac{J}{s}$$

This change in enthalpy is the most energy that the air being input into the system could impart onto the turbine to produce power and it is this value that is compared to the actual energy output by the turbine to calculate the turbine efficiency. This equation can also be used with the recorded outlet temperature to find the actual change in enthalpy for the system that will corroborate the value for the electrical work. The value for the actual change in enthalpy is 24.240 J/s. The calculation for the energy output by the generator that will be represented as W_e for the electrical work

$$W_e = 3^{0.5}(6.6)(2.137) = 24.429 \frac{J}{s}$$

V and A representing the recorded values for volts and amps respectively. While the value for the actual enthalpy change should not be lower than the electrical work this slight difference can be attributed to minor error in the data. With this value calculated the turbine efficacy of the Tesla turbine is then found by taking the absolute value of the actual work provided by the turbine, W, divided by the potential energy that is delivered to the system, $(\Delta H)_{isen}$, and multiplied by 100 to get the percent shown below.

$$\left| \frac{24.429}{-395.275} \right| x100 = 6.18\% \; turbine \; efficiency$$

Sample calculation for non-ideal gas

Data from run 7

The only difference when calculating the thermodynamic efficiency of the turbine without the assumption of ideal gas is the addition of the generalized correlations when calculating the change in enthalpy that requires the calculation of the generalized correlations for both the enthalpy and entropy of the system. This process begins with the calculation of the inlet reduced temperatures for use in Lee/Kesler generalized correlation tables by using the critical temperature and pressure of air, T_c (K)=132.2 and P_c (Bar)=37.45 respectively, in the manner below

$$T_{r_1} = \frac{295.65}{132.2} = 2.2364 \quad P_{r_1} = \frac{2.599}{37.45} = 0.069$$

Through double-interpolation of the Lee/Kesler table a value of -0.0162 is found for ${H_1^R}/{RT_c}$ that can then be reduced to the generalized correlation H_1^R by multiplying by the gas constant and critical temperature of air that is shown below

$$H_1^R = (-.0162) \cdot (8.314) \cdot (132.2) = -17.772 \ \frac{J}{mol}$$

This leads to the calculation of the calculation of the initial entropy correlation by using the residual inlet conditions to again double interpolate using the Lee/Kesler correlation tables. This results in a value of -.0061 for ${S_1^R}/{R}$ that is then multiplied by the gas constant to arrive at the initial entropy correlation S_1^R

$$S_1^R = (-.0061) \cdot (8.314) = -0.051 \ \frac{J}{mol \cdot K}$$

For an initial estimate of S_2^R the outlet temperature is estimated to be equal to that calculated using the same means as those in the ideal gas calculations and the outlet pressure is the atmosphere that leaves the reduced temperature and pressures as

$$T_{r_2} = \frac{225.535}{132.2} = 1.706 \quad P_{r_2} = \frac{1.013}{37.45} = 0.0270$$

This results in a value of -0.00272 gathered from the Lee/Kesler tables for $\frac{S_2^R}{R}$ that is reduced to the second correlation by multiplying by the gas constant shown below

$$S_2^R = (-0.00272) \cdot (8.314) = -0.0227 \ \frac{J}{mol \cdot K}$$

. As stated before the two generalized correlations for entropy are input into the equation for the change in entropy assuming an isentropic case such that the change in entropy will be zero that is rearranged below to solve for the outlet temperature as was the case for ideal gas using goal seek in Microsoft Excel

$$(AlnT_{isen} + BT_{isen} - 0.5DT_{isen}^{-2}) - (AlnT_{in} + BT_{in} - 0.5DT_{in}^{-2}) = ln\frac{P_{out}}{P_{in}} + S_2^R - S_1^R$$

This new outlet temperature found using the generalized correlations is used to re-calculate the residual temperature that is used along with the Lee/Kesler Tables to find a value for S_2^R and if this value is close enough in value to the first value of S_2^R it is not necessary to re-evaluate the outlet temperature again.

$$T_{r_2} = \frac{220.810}{132.2} = 1.670$$

The new reduced temperature results in a value of -0.00313 for $\frac{S_2^R}{R}$ that is reduced to the correlation as follows

$$S_2^R = (-0.00313) \cdot (8.314) = -0.026 \ \frac{J}{mol \cdot K}$$

This is a small enough change that the new outlet temperature can be considered correct and the new reduced value be used to calculate the second correlation for enthalpy. The new reduced temperature results in a value of -0.000805 for $\frac{H_2^R}{R \cdot T_c}$ that is reduced to the correlation below

$$H_2^R = (0.000805) \cdot (8.314) \cdot (132.2) = -0.8848 \ \frac{J}{mol}$$

Finally a new change in enthalpy is calculated using the generalized correlations for enthalpy just calculated that results in the following equation

$$(\Delta H)_{isen} = n * R * (\left(AT_{isen} + \frac{B}{2}T_{isen}^2 - \frac{D}{T_{isen}}\right) - \left(AT_{in} + \frac{B}{2}T_{in}^2 - \frac{D}{T_{in}}\right) - 0.8848 + 17.772)$$

$$= -362.408 \ \frac{J}{s}$$

The efficiency resulting from this new change in enthalpy being

$$\left|\frac{24.429}{-394.557}\right| \cdot 100 = 6.19\% \ turbine\ efficiency$$

Sample calculation for efficiency at high operating pressure

For the turbine described in reference 2 it is known that during a run the actual work produced will be 139.3W of electrical work. It is also known that the conditions with which the turbine is run are at a pressure of 65 psig with a flow rate of 10.95 SCFM. If it is assumed that the turbine is operated at room temperature or approximately 20°C (293 K) then the isentropic work produced by the turbine can be calculated in order to find the turbine efficiency at this high operating pressure.

As with the previous sample calculations for the turbine efficiency with the assumption of ideal gas it is first necessary to obtain a value for the isentropic output temperature by rearranging the equation for the change in entropy. For the isentropic case the change in entropy would be zero and the resulting rearranged equation would be the equation shown below and the isentropic temperature solved for with goal seek in Microsoft Excel is 179.67 K.

$$(AlnT_{isen} + BT_{isen} - 0.5DT_{isen}^{-2}) - (Aln * 293 + B * 293 - 0.5D * 293^{-2}) = ln\frac{14.7}{79.7}$$

The next step is to convert the flow rate from SCFM to a molar flow rate as shown below

$$10.95 * \frac{ft^3}{min} x \frac{0.0283\, m^3}{ft^3} x \frac{1.19\, kg}{m^3} x \frac{min}{60\, sec} x \frac{mol}{0.02897\, Kg} = 0.212\, mol/s$$

The isentropic work can then be calculated using the equation for the change in enthalpy using the calculated isentropic outlet temperature and molar flow rate that results in

$$(\Delta H)_{isen} = .212 * 8.314 * \left(\left(A * 179.67 + \frac{B}{2}179.67^2 - \frac{D}{179.67}\right) - \left(A * 293 + \frac{B}{2} * 293^2 - \frac{D}{293}\right)\right)$$
$$= -691.090\, \frac{J}{s}$$

The actual electrical work produced by the turbine can then be divided by the isentropic change in enthalpy to calculated the turbine efficiency

$$\left|\frac{139.3}{-691.090}\right| x100 = 20.16\%\ turbine\ efficiency$$

Closed-loop Hybrid

Tesla Turbine

Warnings – read before use

It is important to understand that this turbine is an experimental device. It is not intended to be used for prolonged periods or to be permanently used. If you do use the turbine for this function, use at your own risk.

- Make sure that all the screws are tightened before use
- Make sure the grub screws on the generator coupling are particularly tight as they will be spinning at high speed.
- Always use eye protection/goggles when using the turbine.
- It is recommended that the RPM is monitored when running under no/little load. This can be achieved by using a multi-meter with a Hz option.
- After longer periods of use or possible stress check the bearings for damage or wear.
- The bearings have a ‘slide on’ fitting making them easy to remove/replace/change; however this means it is possible that the bearing will spin in the housing at very high speeds or over longer running times. This would cause damage to the housing after prolonged use. If you intend to run the turbine for longer periods or high speed it is recommended the bearings are sealed (a special glue) using a bearing sealant.
- Do not touch the bulbs while running they will be very HOT
- Do not touch the motor or shaft while running
- Do not touch or put anything close to the electrics, board or bulb holder while running. The underside of the bulb holders (board) is **electrified** while in use. Although at only a low voltage.
- Under extreme pressures and stress Tesla stated that disks are liable to warp. It is unlikely to happen on this version but please be aware that it is possible.
- The turbine is designed for use with compressed air but with steam, water and hot gases in mind. Proceed at your own risk.

Specification

Sizes	
Turbine diameter:	100mm
Turbine length (including generator):	120.75mm
Blade/disk diameter:	78mm
Blade/disk thickness:	1.2mm
Blade/disk gap:	1.5mm
Number of Blades/disks:	5
Over base size:	180mm x 110mm
Materials Used	
Case :	6082 aluminium
Spindle :	303 stainless steel
Disk Spacers :	6082 aluminium
Injector :	CZ121 brass
Connectors	
Inlet :	1/4 BSP (British Standard Pipe)
Outlet :	1/4 BSP (British Standard Pipe)
Adapters (supplied) :	Uni connector
Generator	
type :	3 phase AC
MAX Output :	150 watts
Interesting features	
Reversible:	Yes, using flat screwdriver
Design improvements:	Injector system and modular designs
Replaceable parts:	Motor can be upgraded Bulbs can be changed or removed
Possible experiments:	New design for injector new disks, amount of disks different mediums different generators
Free spare:	free 'blank' injector that can be redesigned
Medium:	Compressed air, vacuum. Steam, hot gasses such as R134a or even water.

New Tesla Metal Turbine – Closed Loop, Hybrid, Ceramic Bearings and Higher Efficiency

Once again this Tesla turbine is eagerly awaited. Further improvements have been made after plenty of R&D from the last turbine. The turbine efficiency has been increased by increasing nozzle pressures and added shaped spacers that act like an **impulse turbine** AFTER the useful energy has be captured using the discs. This may not be that satisfactory to some Tesla purists that don't think that impulse turbine technology should be mixed with the Tesla turbine but it does increase performance and they can be removed if required and replaced with your own spacers/washers.

There is plenty of interest in using Tesla turbines with **organic rankine cycle systems**, to enable power generation with **waste heat** or **solar power**. A number of major changes have been made to make this turbine useable in a closed-loop system (working fluid is constantly reheated and cooled). In the other words no air, gas, steam, water can escape. It is now sealed ready for use in pressured system. **It has been tested at 150psi using air.**

The turbine still has a standard a 1/4" BSP threaded connector for both the inlet and outlet pipes. A 1/4" BSP to Universal (uni) adapter is provided to allow easy connection to an air compressor (5+ **SCFM** recommended). The turbine comes with a 3 phase generator and 3 x 20 watt bulbs so that a load can be drawn, this generates 60 watts. The generator can produce up to 150watts leaving plenty of headroom for experimentation. The turbine design and generator mount allows for possibility of changing the generator or connecting to something else. The turbine is supplied on a aluminium base for display and demonstration purposes (connected using two M6 Hex cap screws).

History of Tesla Turbines

A Tesla turbine is a quite unique technology. It was invented and patented by **Nikola Tesla** on the 21st October 1909 at the United States Patent Office from experiments done in England. The US patent **1061206** was granted on the 6th May 1913, although historical documents suggest that that Tesla first showed a 200 horsepower (about 150kw) 16,000 RPM version on the 10th of July 1906 (on Tesla's 50th birthday).

From what Tesla wrote in the patent it seems his experiments were mainly done with fluids but had confirmed it works with air as well. Tesla had his own personal requirements for a generator for his laboratory. You have to remember use of electrical power was still in its infancy which Tesla played a critical role developing many of the electrical components we now take for granted. Typically Tesla found his alternative and better way of generating power, using a steam boiler powering a tesla turbine which in turn powered an AC generator.

Unlike conventional turbines, jet engines and most pumps, Tesla's turbine can be designed to be reversible with no loss in efficiency. Normally compressed air, fluids or steam is applied to the inlet and the turbine spins giving a mechanic rotational output. However, it can also double up as a pump, by rotating the shaft the air/fluid/steam can and be sucked and blown from the inlets / outlets. This makes it unique in being a reversible turbine and a reversible pump. However efficiency increasescan be made by tailoring the pump to the medium. In other words an air powered turbine may have some slight design changes compared to water powered turbine.

Sadly unlike the work done with electricity the Tesla turbine never became popular and was simply forgotten about. Only in the last few years has there been new interest.

Tesla turbines are also known as cohesion turbines, bladeless turbines, boundary layer turbines and Prandtl layer turbines.

Working with Air, Steam, Water, Vacuum and Hot Gases

This turbine is ideal for experiments with air, steam, water and hot gases. With air or a Vacuum no special precautions need to be undertaken. With hot gases ensure the generator housing (and hence generator) does not over heat; prolonging the generator life. Try to keep the temperatures below 100C. I would suggest trying heat sinks and cooling-jackets around the generator casing. With steam and water mount the turbine so the generator is vertical and facing upwards (at the top). This means if any water does get into the generator compartment it can return back into the main compartment and outlet over time. If this is still a persistent problem I would suggest changing the bearings for ones with rubber seals (bearings 625-2RS) which will provide extra protection to the generator. With steam and water slowly increase the pressures with each experiment and check the generator housing. The turbine has been tested at 150psi with compressed air. If you do use high pressures please understand the risks and take the appropriate safety precautions.

Key points

- Closed loop - ideal for **organic rankine cycle systems**
- Hybrid Turbine - using Tesla technology and impulse turbine technology to improve efficiency
- Ceramic Bearings - faster, more efficient, high temperatures
- Higher Efficiency
- Runs from air, a vacuum, steam, gases and even water

How to take apart

1. Firstly remove the wires connected to the turbine by removing the nuts.
2. Then remove the second nut under each wire. This frees up the electrical connectors
3. There is knurled ring/part on the turbine (same end as electrical connectors). Undo this but try to keep the connectors (and black disk) from spinning round.
4. Slide the knurled ring off, carefully remove the black disk.
5. The metal tube around/over the generator simply unscrews. Grip by hand and unscrew.

   BTW: Be careful when replacing it as the thread is fine and needs to be perfectly align otherwise you will rip the thread. The generator is now exposed.
6. Unscrew the four small bolts close around the motor.
7. Now unscrew the grub screw on the brass connector (the brass connector connects the turbine to the motor).
8. The generator will slide off.
9. Unscrew the 4 bolts on casing.
10. Carefully slide the front casing off.
11. The rotor and disks will be held in one side of the casing. Carefully remove it.

How to put back together

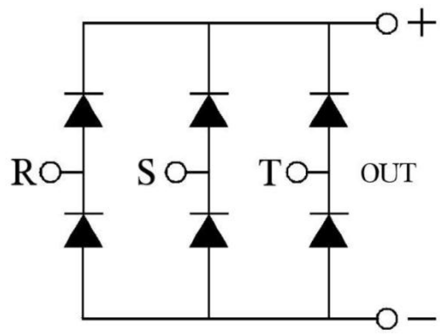
1. When putting back together this MUST do in correct order to get perfect alignment. The turbine will have extra resistance or cease if not done correctly.
2. Lightly slide the rotor/disks into the back casing. Make sure the bearings are correctly seated.
3. Slide the front casing on to the back casing. Make sure the shaft/rotor comes through ok. Make sure there is no dust on the parts where the two casing parts meet. This will ensure a good seal.
4. Check the rotor/disks spin freely.
5. Hand tighten the four bolts to keep the casing together. Now tighten with moderate pressure only. Now tighten with a torque wrench, working in a star-shape pattern until all of the bolts are completely tightened.
6. Prepare to attach the generator to the casing. Hold the generator in your hand. Put the bolts and brass on ready.
7. Align the shaft to the brass connector. Note that the shaft has a flat, align this with the grub screw on the brass shaft connector. LIGHTLY push on. DON'T tighten the grub screw yet. Leave it lose.
8. Align all the bolts to the threaded holes on the casing and hand tighten.
9. Now tighten the four bolts working in a star-shape pattern until all of the bolts are completely tightened.
10. Tighten the grub very slightly on the brass connector (this ensures the shaft is aligned)
11. Spin the generator to make sure it spins freely (it sound spin for a second or two). If it does not spin freely undo everything and repeat.
12. Provided it now spins freely tighten the grub screw quite hard.
13. Screw on the tube to the casing. Make sure it is PERFECTLY aligned. But the casing flat on a table to double check. Screw on slowly to make sure it is not cross threaded.
14. Put the connectors through the black plastic disk.
15. Put on the knurled ring and tighten by hand.
16. Put on a nut on each connector and tighten them. The connector will probably spin so use pliers to hold.
17. Put on the wires and the second nut on each connector

The generator and converting the 3 phase AC to DC output

A 3 phase generator was chosen because of the cost, performance, efficiency, size and ability to run at high speed over its DC equivalents. The generator is an ‘outrunner’, with static coils/windings are in the centre and the magnets rotating around. This allows it to run at very high speeds. The generator is capable of generating around 150watts. The turbine is supplied with 3 x 20 watt lamps to add some load, but these could be increased or even decreased for lower wattage versions. If the bulbs are removed the generator will free-wheel with almost no resistance. Typically the generator will produce 1volt for every 1400rpm. Hence The turbine needs to run at 16,800rpm for 12 volts.

Three bulbs were the easiest way to place a load on the generator for demonstration purposes. However a 3 phase output is not ideal in most cases for a practical output, this can easy be fixed using a bridge rectifier or otherwise known as a diode rectifier. This will create a pulsed DC output, which can be smoothed using capacitors if required.

The circuit required is as follows.



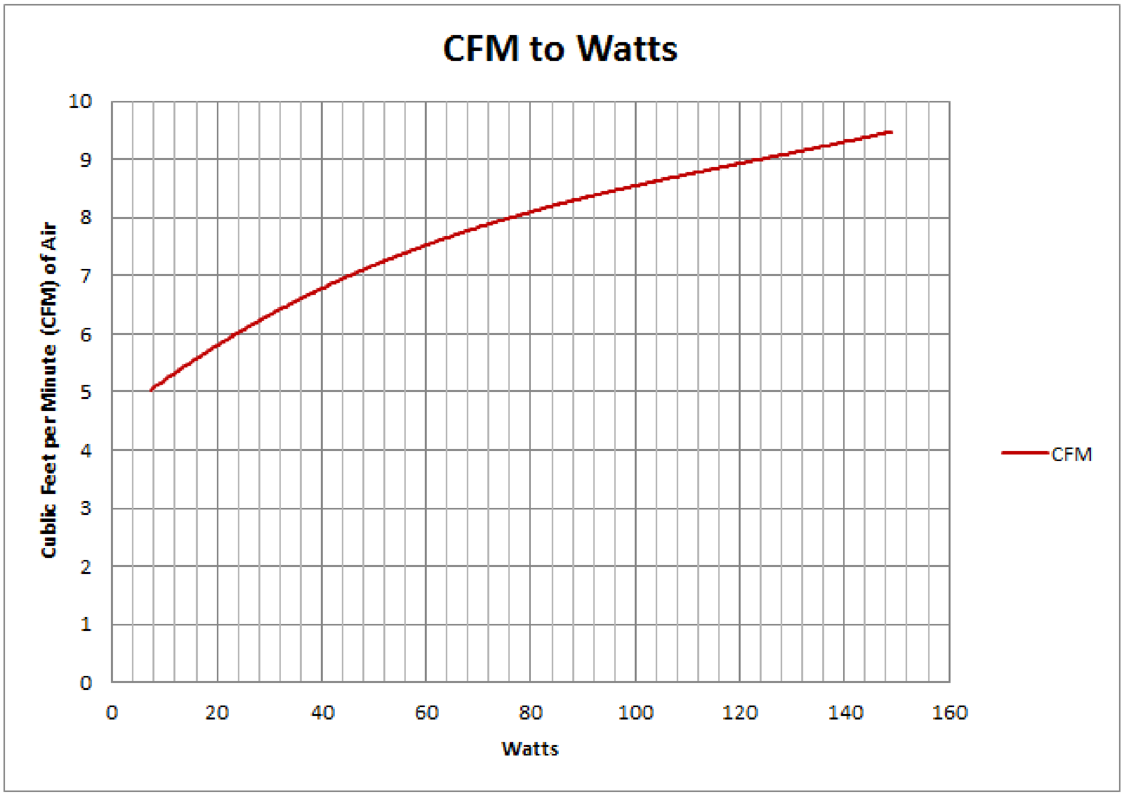
For further information on the subject visit http://en.wikipedia.org/wiki/Bridge_rectifier

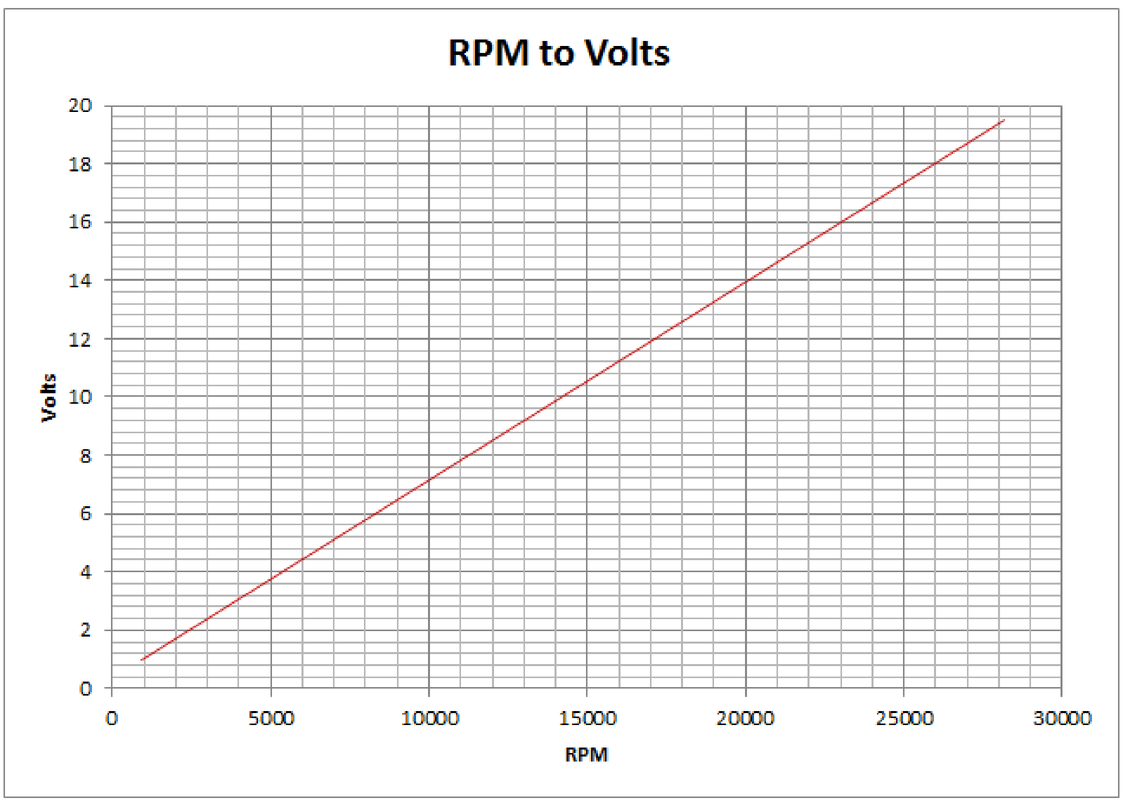
Generator Specification

Max Power	150 Watts
Max RPM (manufacturer suggestion)	20,000rpm
Diameter	27.8mm(1.092”)
Length	28.9mm (1.14”)
Shaft Diameter	4.0mm (.1575”)
Mounting Screw Thread	2.5mm, max depth 4.5mm, on 16mm (.625”) bolt
Max Case Temperature	65 C (149F)
Efficient Operating Current	5-13Aamps

How to contact us

If you have any further questions you may contact Glenn at sales@gyroscope.com
or visit www.gyroscope.com


CFM to Watts
Cubic Feet per Minute (CFM) of Air
10
9
8
7
6
5
4
3
2
1
0
0
20
40
60
80
100
120
140
160
Watts
CFM


RPM to Volts
Volts
20
18
16
14
12
10
8
6
4
2
0
0
5000
10000
15000
20000
25000
30000
RPM